A Search for Core-Collapse Supernovae using the MiniBooNE Neutrino Detector

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We present a search for core-collapse supernovae in the Milky Way galaxy, using the MiniBooNE neutrino detector. No evidence is found for core-collapse supernovae occurring in our Galaxy in the period from December 14, 2004 to July 31, 2008, corresponding to 98% live-time for collection. We set a limit on the core-collapse supernova rate out to a distance of 13.5 kpc to be less than 0.69 supernovae per year at 90% CL.

INTRODUCTION

Supernovae are stars that explode and become extremely luminous. Core-collapse supernovae typically begin as stars with masses greater than $8M_\odot$. When these stars explode, $\sim 3\times10^{53}$ ergs of gravitational binding energy is released in a burst of neutrinos and anti-neutrinos lasting approximately 10 seconds [1]. This neutrino burst will arrive at the Earth several hours prior to photons from the supernova; neutrino detectors can be utilized as the first line of detection for supernovae.

Although current predictions for the rate of supernovae in the Milky Way galaxy are between 1 and 12 per century [2], the last observed supernova in our Galaxy occurred in 1604, in the constellation Ophiuchus [3]. Detection of supernovae using optical telescopes is highly dependent on the orientation of the telescope with respect to the supernova. Neutrino detectors are able to observe supernovae occurring at any point in our Galaxy, regardless of the orientation of the supernova with respect to the detector. Starting in the late 1990's, a net-

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work composed of neutrino detectors has been performing a real-time search for supernovae [4]. When a supernova is observed this network will provide coordinates to observatories across the world, allowing them to align their telescopes in time to observe the photons from the supernova.

Supernova neutrino data can be used to verify astronomical predictions of the stellar collapse model and to provide bounds on standard model quantities. Detection of the neutrinos from SN1987A in the Large Magellanic Cloud by the Kamiokande-II [5] and IMB [6] water Cerenkov experiments provided upper limits on the lifetime and mass of the $\bar{\nu}_e$ that were comparable to results from laboratory-based experiments at the time [1].

Several neutrino detectors have published results from their search for supernovae occurring in our Galaxy [7]. The LVD detector, located at the Gran Sasso Underground Laboratory in Italy, set an upper limit of 0.18 supernovae per year in our Galaxy at 90% C.L., for 14 years of run-time, from 1992 to 2006 [8]. The Super-Kamiokande experiment in Japan set a limit of less than 0.32 supernovae per year at a distance of 100 kpc, at the 90% CL for the period of time of May, 1996 to July, 2001 and December, 2002 to October, 2005 [9]. MiniBooNE's search covers a more recent period of time, from December, 2004 to July, 2008.

THE MINIBOONE EXPERIMENT

MiniBooNE is a neutrino experiment designed to search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ neutrino oscillations, using a beam of neutrinos produced by the Booster beamline at Fermi National Accelerator Laboratory [10]. The MiniBooNE detector is a spherical tank of inner radius 610 cm, filled with 800 tons of mineral oil (CH_2) [11]. An optical barrier divides the detector into two regions. The inner region contains 1280 inward-facing photomultiplier tubes (PMTs), providing 10% photocathode coverage. The outer region is lined with 240 PMTs that provide a veto for charged particles entering or leaving the tank, such as cosmic rays [12]. The detector is buried 3 meters underground, at a sufficient distance to eliminate the majority of incoming cosmic ray hadrons. However, a 10 kHz rate of cosmic ray muons can still penetrate this barrier, and their progeny are the main source of background for the supernova search.

THEORETICAL PREDICTIONS

The prediction for the observation of a supernova signal in MiniBooNE is based on the following assumptions [13]:

- The event is a core-collapse supernova.
- When the core collapses and rebounds, the change in the gravitational binding energy is $\sim 3 \times 10^{53}$ ergs.
- Each of the 6 types of neutrinos $(\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau)$ carry away 1/6 of this binding energy.
- The neutrinos are emitted during a 10 second burst.
- The neutrinos are emitted isotropically.
- The neutrinos produced during a supernova core collapse have the following average energies and temperatures [2]: $\langle \mathrm{E}_{\nu_e} \rangle \approx 10$ MeV and $T \approx 3.5$ MeV, $\langle \mathrm{E}_{\bar{\nu}_e} \rangle \approx 15$ MeV and $T \approx 5$ MeV, and $\langle \mathrm{E}_{\nu_{other}} \rangle \approx 20$ MeV and $T \approx 8$ MeV, where other is $\nu_\mu, \bar{\nu}_\mu, \nu_\tau$, and $\bar{\nu}_\tau$.
- The spectrum for supernova events is characterized by a Fermi-Dirac distribution with zero chemical potential.

The charged current (CC) interaction, $\bar{\nu} + p \to l^+ + n$ and $\nu + n \to l^- + p$, is used to search for the supernova signal in MiniBooNE. The ν_{other} aren't energetic enough to engage in this interaction. The $\bar{\nu}_e$ reaction will dominate the event sample in our detector, due to the larger cross section of this interaction on free protons present in the CH_2 molecules in mineral oil. Therefore, higher-energy $\bar{\nu}_e$s are the primary constituent of the detectable supernova neutrino signal in MiniBooNE.

The predicted supernova rate in MiniBooNE assumes a maximum usable detector radius of 550 cm, 25 cm inside the optical barrier. Event locations are reconstructed from light intensity and timing information from the PMT array.

Predicted Signal

The number of expected signal events is described by:

$$N = 11.8 \left(\frac{E_B}{10^{53}\mathrm{erg}}\right) \left(\frac{1\mathrm{MeV}}{T}\right) \left(\frac{10\mathrm{kpc}}{D}\right)^2 \left(\frac{M_D}{1\mathrm{kton}}\right) \left(\frac{\langle\sigma\rangle}{10^{-42}\mathrm{cm}^2}\right), \tag{1}$$

where E_B is the binding energy released during the supernova, T is the temperature of the emitted $\bar{\nu}_e$, D is the distance to the supernova, M_D is the fiducial mass of the detector, and $\langle\sigma\rangle$ is the thermally averaged free proton cross section for $\bar{\nu}_e + p \to e^+ + n$.

The two parameters, T and E_B, have uncertainties associated with them. Observational limits set by SN1987A constrain the amount that one can vary these parameters individually and simultaneously. For individual variations, E_B varies between 2×10^{53} and 3×10^{53} ergs, and the temperature lies between 4 and 6 MeV [14]. A

Symbol	Meaning	Value
E_B	Gravitational binding energy of Supernova	3×10^{53}ergs
T	Temperature of incoming neutrinos	5 MeV
D	Distance of core-collapse supernova from Earth	10 kpc
$\langle\sigma\rangle$	Thermally-averaged cross section in mineral oil	54×10^{-42}cm^2
M_D	Fiducial mass of the detector	0.595 ktons @ r = 5.5 m
M_D, final event selection		0.326 ktons @ r = 4.5 m

TABLE I: Symbol information for Equation 1

discussion of the systematic error assigned to our result due to these parameters is presented later.

Using the parameter values listed in Table I, 226 of these events are expected in MiniBooNE with a reconstructed lepton energy of 0-60 MeV, using a fiducial detector radius of 550 cm and prior to any event selection cuts [13].

The neutral current interaction, ^{12}C(ν, ν')^{12}C* (15.11 MeV), produces a 15.11 MeV photon that appears electron-like in our detector. This interaction may increase our event rate by ~23 events [15]. However, this number is less than the uncertainty on the prediction due to the temperature [16], and thus this interaction channel is not included in this analysis.

By assuming neutrino emission parameters consistent with SN1987A data, the predicted number of signal events includes effects due to neutrino mixing prior to arrival at the MiniBooNE detector.

Predicted Sources of Background Events

The decay products of cosmic rays are predicted to be the only source of background to the supernova signal [13]. They produce two distinct backgrounds to this search: Michel electrons and ^{12}B. Stopped cosmic ray muons occur in the detector at a rate of 2 kHz. Approximately 95% of these stopped muons will decay to Michel electrons or positrons whose energy spectrum has an endpoint of 52.8 MeV. With trigger-level cuts applied, the rate of these background events is reduced to 2 Hz.

Forty-four percent of the 2 kHz of stopped cosmic ray muons are μ^-. Eight percent of these μ^- will capture on ^{12}C nuclei in the detector's mineral oil, of which 16% will become particle unbound states of ^{12}B. This isotope of boron is unstable to β^- decay. The electrons produced in this interaction occur with a frequency of 11 Hz (=2 kHz $\times$ 0.44 $\times$ 0.08 $\times$ 0.16), and have an energy spectrum with an endpoint of 13.9 MeV.

The MiniBooNE supernova search avoids the need for any detailed knowledge of the backgrounds, as further explained in the Results section.

ANALYSIS DETAILS

The supernova search was performed on data spanning the period from 12/14/2004 to 07/31/2008. The data are broken down into runs that typically last a few hours. Runs are composed of events, each lasting 19.6 microseconds and triggered by a particular set of conditions being met by the PMT and external signals. It is prohibitively time consuming to apply the complete set of event selection cuts to every 10 second window of events in this data sample. This problem is circumvented by performing two passes over the data. The first pass over the data applies low level cuts that remove time windows with low event counts. The second pass applies quality cuts based on reconstructed quantities to isolate the predicted supernova signal from expected background sources.

Event Selection Cuts: First Pass

The first pass over the data must meet two requirements: the beam-off activity trigger, and a data quality filter. The beam-off activity trigger separates potential supernova neutrino events from events occurring in the detector from other sources. It is set when the following conditions are met:

- Time since last neutrino beam event > 20 μs.
- Number of inner detector PMT hits $\geq$ 60.
- Number of veto region PMT hits < 6.
- The time since the number of tank hits is $\geq$ 100 is $\geq$ 15 μs, and the time since the last activity in the veto region is $\geq$ 15 μs.

The first condition functions as a filter to remove neutrino beam data. The second condition serves as a lower bound on the detected energy. The third and fourth conditions reject cosmic ray muon events and temporarily disable data recording for 15 μs, enough time for a muon ($\tau_\mu \approx 2.2$ μs) to decay and its decay products to cease interacting in the detector. The data quality filter reduces our live time by 2%.

The total data set consists of 6997 runs. After selection, the data are further split into 10 second intervals. These are sliding intervals; each event within a run starts

a new 10 second window. The number of events per 10 second window is recorded and histogrammed. Let μ and σ denote the mean and the standard deviation of this histogram, respectively. Any run containing a 10 second time period with more than Z events, where Z = $\mu + 5\sigma$, is identified as containing a potential supernova candidate and selected to continue to the second pass.

The examination of runs not selected provides a measure of the background distribution of events. The background distribution of events at this stage of the analysis has a mean of $\mu\approx100$ and a standard deviation of $\sigma\approx10$ events, per 10 second window (See Figure 1). These numbers have remained stable throughout the MiniBooNE data collection period for all runs, rejected and selected, in the beam-off activity sample. This first pass selects time windows containing greater than Z=150 events per 10 second window. This serves to greatly reduce the dataset, in preparation for the next step of the analysis.

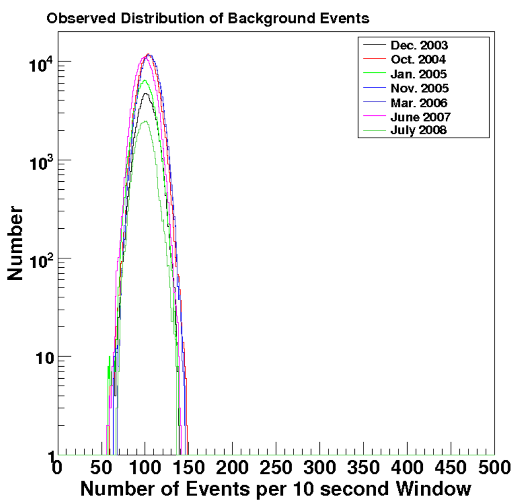

FIG. 1: Number of background events per 10 second window passing the beam-off activity trigger and the data quality filter for runs spanning our entire data sample, broken into time intervals. Runs shown were not selected during the first pass. Each shape contains $\approx10^5$ 10 second windows.

Event Selection Cuts: Second Pass

After potential supernova candidates are identified using the first pass over the data, event selection cuts are used to isolate the potential supernova signal from the background events.

The number of bursts of light, separated by time within an event, are referred to as sub-events. More than one sub-event is indicative of multiple interaction products. Only one burst of light will be created in the detector from positrons produced by the $\bar{\nu}_e$ CC interaction. The number of veto PMT hits must be less than 6, to remove potential cosmic ray events. The number of tank hits is roughly proportional to the energy of the particles interacting inside the detector. The possible range of tank hits for a supernova signal is 50 to 200. Any number above 200 is more indicative of a μ in the detector, and any amount lower than 50 is indicative of a low energy background event.

Energy cuts based on the expected Michel electron and ^{12}B backgrounds are applied to further reduce the number of background events. An energy cut of 11-45 MeV allows for minimal loss of signal while maintaining a fairly large signal to background ratio. Finally, the neutrino interaction must take place in the inner 450 cm of our detector. This more restrictive fiducial requirement removes low-energy background events that penetrate from the outside of the detector.

A summary of the cuts applied during the second pass is:

- Beam-off activity trigger.
- Data quality filter.
- 1 burst of light (subevent).
- Number of veto region PMT hits < 6.
- $50 <$ Number of inner region PMT hits < 200.
- Reconstructed radius < 450 cm.
- 11 MeV $<$ Reconstructed lepton energy < 45 MeV.

The effect of these cuts is to reduce the expected number of supernova events from 226 to 110 for a supernova at a distance of 10 kpc.

After these cuts are applied, the data are split into 10 second intervals, and the same selection procedure as applied in the first pass is repeated. The examination of runs that are not selected indicates the background distribution at this stage of the analysis has a mean of $\mu\approx20$ and a standard deviation of $\sigma\approx4$.

RESULTS

During the first pass through the data, we identify 319 out of 6997 run numbers as containing potential supernova candidates. The data from these runs are processed using the full set of cuts, and 78 of the 319 runs remain.

The distribution of the number of events per 10 second window for all 78 remaining runs is shown in Figure 2, with a mean of 20.11 events and a standard deviation of 4.43 events. There are no cases where >51 events per 10 second window are observed.

The background event estimate is determined by examining time windows in the beam-off trigger stream that

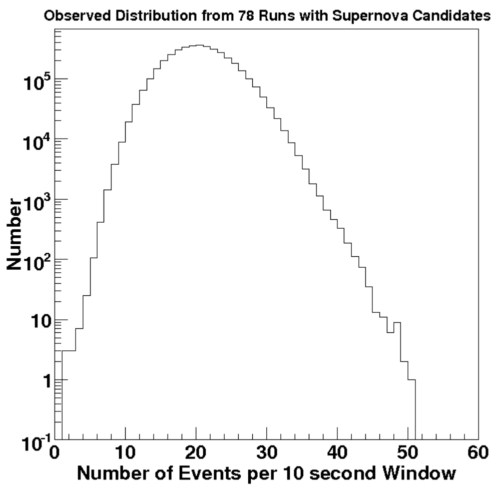

FIG. 2: Distribution of the number of neutrino events per 10 second window, for all 78 runs identified as containing potential supernova candidates. There are no windows with greater than 51 total events per window.

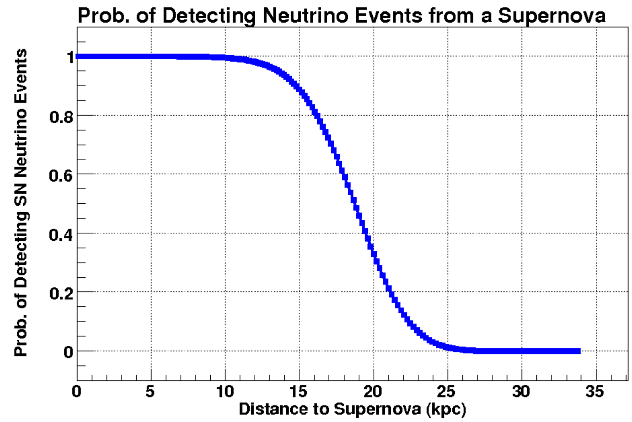

FIG. 3: Probability of detecting a supernova as a function of distance in kpc. A fiducial radius of 450 cm and the efficiency of the event selection cuts are included. Statistical and systematic errors are included.

pass the data quality filter, but that are not selected during the first pass. The entire set of event selection cuts are applied to a set of runs spanning the entire collection period, from December, 2004 through July, 2008. The mean of the distribution is 20.34. Therefore, we set a limit for supernova observation based on (52 - 20.34), or 32 signal events.

One hundred and ten signal events are expected from a supernova occurring within 10 kpc of MiniBooNE, after applying all event selection cuts. The null result is used to place a limit on the probability that a supernova occurred during our search window. This approach, though conservative, has the benefit of not requiring a prediction for the background energy distribution. The null observation of 32 events allows us to set a limit for a distance greater than 10 kpc. Equation 1, which describes the relation between expected events and distance from the supernova, is adjusted to account for efficiency of the event selection cuts. The number of expected events represents the mean of a Gaussian, with a root-mean-square of $\sqrt{\mathrm{N}}$, or the statistical error on N. The uncertainty on this number is driven by uncertainties on the two parameters, T and E_B. The free proton cross section is proportional to T^2, making Equation 1 proportional to $T \times E_B$. Simple error propagation results in a systematic error of 0.36N. However, the observation of SN1987A constrains the amount that T and E_B can fluctuate simultaneously. Consequently, the total systematic error assigned is 0.26N.

The detection probability was formed by calculating the probability that the Gaussian with a mean of N and root-mean-square of $\sqrt{N + (0.26N)^2}$ could fluctuate down to 32. Figure 3 shows the calculated detection probability, as a function of distance to the supernova. The limit is set at the point where our detection efficiency drops to 95%. Our limit of 32 signal events corresponds to a distance of 13.5 kpc. This limit increases to 16.2 kpc in the absence of systematic errors.

Using a Poisson probability distribution, the observation of 0 events over one collection period allows us to set a limit of 2.3 supernovae at the 90% CL. Following the example of the Super-Kamiokande search [9], we set a limit using the number of total live days in our data sample. The data sample used in this analysis corresponds to 1221.44 live days. Therefore, we set a limit at the 90% CL on a supernova having occurred within 13.5 kpc of our detector, at a rate of 0.69 supernovae per year. This limit corresponds to 73.8% coverage of the Milky Way [17].

CONCLUSIONS

The search for supernovae using neutrino detectors is complementary, and in many ways superior, to searches performed using telescopes. Using the MiniBooNE detector, we performed a search for supernovae using data taken between the period from 12/14/2004 to 07/31/2008. A limit is set on the rate of core-collapse supernovae in the Milky Way within a distance of 13.5 kpc from the Earth to be less than 0.69 supernova per year at the 90% CL. This limit corresponds to 73.8% coverage of the Milky Way [17].

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